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The Condition of High-Velocity Ductile Fracture

E. OROWAN

Technical Report No. 4
Office of Naval Research
Contract Number N5ori-07870

July 1954

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THE CONDITION OF HIGH-VELOCITY DUCTILE FRACTURE

TECHNICAL REPORT NO. 4

By E. OROWAN

Office of Naval Research
Contract Number N5ori-07870

Massachusetts Institute of Technology
Department of Mechanical Engineering

D. I. C. 6949

July 1954

THE CONDITION OF HIGH-VELOCITY DUCTILE FRACTURE

1. Elastic-elastic instability.

T. W. George ⁽¹⁾ observed some time ago that a large sheet of thin aluminum foil, provided at its center with a knife-cut crack, burst under tensile load with a suddenness usually associated with brittle fracture. Although genuine cleavage fracture has never been observed in aluminum, and the tensile fracture of the aluminum foil was of the common ductile type preceded by necking, the phenomenon observed by Irwin and George has much in common with brittle fractures. When necking starts, plastic deformation ceases elsewhere in the foil; the deformation in the neck is confined to a narrow strip, the width of which is of the order of the foil thickness. When the crack starts to propagate along the neck from the ends of the initial knife-cut gash outwards, practically all of the work required for extending it is plastic work concentrated in a narrow belt adjacent to the outlines of the crack; Fig. 1 shows by shading the plastically distorted zones of necking which later become the outlines of the propagating crack. Since the width of the distorted zone is small compared with the length of the crack, the plastic work per unit length of the crack outlines can be treated on the same basis as the surface energy of the crack walls in the Griffith theory; an exactly corresponding treatment for the brittle fracture of ductile steels has been given by the present writer ⁽²⁾. Consequently, the fracture of a thin ductile foil can be treated by means of the Griffith energy criterion, although the fracture mechanism is essentially ductile.

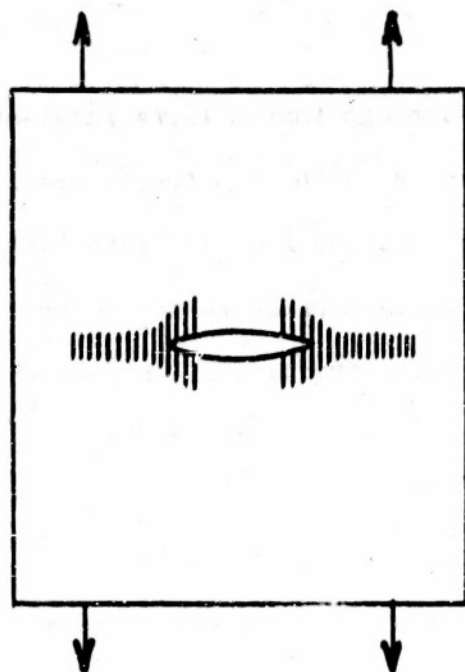


Fig. 1

While the case of the aluminum foil represents an essentially brittle fracture with a narrow zone of plastic deformation playing the role of the surface energy in the Griffith theory, instances of essentially ductile fractures progressing with high velocity are also quite common. Tensile tests on ductile metals usually end with a sharp bang due to acceleration to high speed the elasticity of the testing machine. If the specimen is

very long, its own elasticity can produce the same effect.

The fact that the elasticity of the specimen can cause high-velocity crack propagation even if the fracture mechanism is basically ductile has led to the suggestion ⁽³⁾ that such processes would be governed by the Griffith energy criterion of fracture ⁽⁴⁾, according to which fracture occurs when the work dW required for extending the length c of the crack by a small amount dc is just covered by the accompanying release $-dU$ of the elastic energy U stored in the specimen:

$$dW = -dU \quad (1)$$

This form of the Griffith principle applies to the case where the process of extension of the crack by dc takes place while the

specimen is held between rigidly fixed grips. For the treatment of the case where the crack propagation is assumed to occur at constant load, and for a general discussion of the Griffith criterion see reference (5).

On the other hand, it can be demonstrated ⁽⁵⁾ that the Griffith criterion is applicable only to essentially brittle fractures, i.e., to fractures where plastic deformation is either absent, or confined to a thin layer at the walls (in a foil, the outlines) of the crack while the bulk of the specimen is purely elastic. This can be recognized already from the circumstance that a typical ductile fracture, such as the cup-and-cone or the shear type fracture of a ductile metal, progresses by plastic deformation practically uninfluenced by the values of the elastic moduli. It would take place in the same way if the moduli were infinitely high; in this case, however, the right hand side of eq. (1) would vanish, and the equation could not be satisfied.

Since the energy criterion eq. (1) cannot be applied to essentially ductile fractures, the question arises, what is the condition for the self-acceleration of a ductile fracture by the release of elastic energy in the specimen or in structures connected in series with it, such as a testing machine?

Let Fig. 2 represent a long tensile specimen in which at the point C, a ductile crack, or a neck leading to cup-and-cone fracture, develops. Fig. 3 gives schematically the load vs. plastic extension curve of the specimen: its abscissa is the increase of the "natural length", i.e., of the length measured after removing the load and with it the elastic extension. Initially, the load

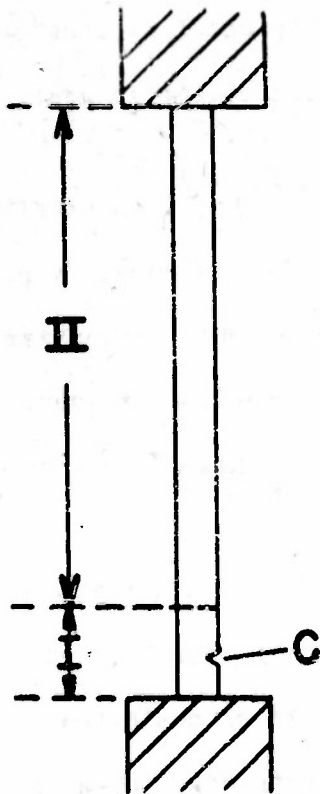


Fig. 2

increases; however, when necking starts, or when the crack has progressed to a certain depth, a load maximum (the "ultimate stress") is reached, and then the load drops with further extension. The maximum of the curve is a point of "plastic instability", beyond which the load required for plastic deformation decreases.

In addition to the plastic extension, the specimen also suffers elastic extension. The former is localized around the neck of the crack; to the latter, all parts of the specimen contribute. In the cases when rapid fracture driven by the release of elastic energy is likely to be

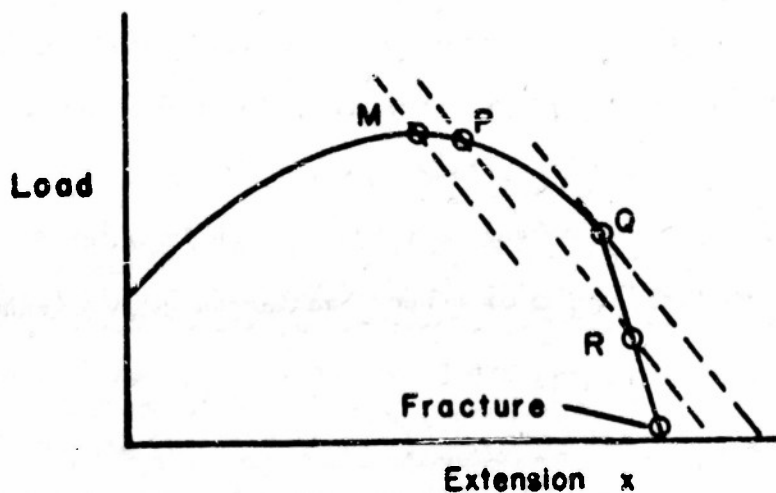


Fig. 3

noticeable the specimen is very long, so that the elastic extension of the plastically deforming region I is negligible compared with that of the purely elastic region II; this means that the spring constant of the specimen is identical with that of the elastic portion II and therefore remains practically constant during the propagation of the crack or the contraction of the neck. The elastic extension is then proportional to the load. Suppose now that the specimen is extended to the point P and then the grips are held rigidly fixed, so that any further plastic extension of I has to take place at the cost of an equal decrease of the elastic extension in II. In the course of this process, the stress must drop according to the elastic relationship,

$$dF = -C \cdot dx \quad (2)$$

where dF is the change of the load, C the spring constant, and dx the increase of the plastic extension in region I, so that $-dx$ is the change of the elastic extension of region II. In Fig. 3, the dashed line through P represents the elastic release of load that accompanies a virtual plastic extension of the specimen between fixed grips. With the assumed value of C , the load would drop more rapidly than the force required for further plastic yielding, so that the condition is stable and no plastic extension can take place unless the grips are moved apart. However, with further extension the point P, moving along the plastic curve, arrives at the position Q where the elastic load release line is a tangent to the curve. At Q, the condition of the specimen becomes unstable; any further extension

leads to a point R at which the yield load drops more rapidly with further plastic extension than the load available after elastic release. Beyond Q, therefore, the specimen is unstable and fractures with high velocity under its own elastic tension. The point Q marks the beginning of the "plastic-elastic instability"; plastic instability, defined by the drop of the yield load, starts already at M. The longer the specimen, the lower the value of the spring constant C, and thus the slope of the elastic load release line. With decreasing C, therefore, the point of plastic-elastic instability Q moves towards that of plastic instability M; in the limiting case of an infinitely long specimen (or of infinitely high "elastic compliance" $1/C$ of the spring connected in series with the specimen), the two points coincide.

The point of plastic-elastic instability is of importance in testing: if a testing machine is not "hard" enough, elastic instability occurs soon after the load maximum, and the load-extension curve cannot be followed much beyond this point. Weight-loading and hydraulic machines, of course, have a tendency to "run away" already at the load maximum; however, if the machine is otherwise rigid enough, the descending branch of the load-extension curve can be followed at least approximately by the use of stops for interrupting the extension.

2. The analytic condition of plastic-elastic instability.

The geometrical condition of instability explained in Fig. 3 can be translated into an analytic form. Let dW be the plastic work of crack propagation or neck contraction during an increment dx of

the plastic extension; if the yield force is F ,

$$dW = F \cdot dx$$

or

$$F = \frac{dW}{dx} . \quad (3)$$

Consider now the purely elastic part II of the specimen (Fig. 2); for simplicity, let it be assumed that all but an insignificant fraction of the elastic energy is contained in it. Since the specimen is between fixed grips, the extension dx of the plastic part I causes contraction of the elastic part by $-dx$. If G is the tensile force in the elastic part and U the elastic energy,

$$dU = -G \cdot dx$$

or

$$G = -\frac{dU}{dx} \quad (4)$$

If the specimen is in equilibrium, $F = G$ and so

$$\frac{dW}{dx} = -\frac{dU}{dx} \quad (5)$$

or

$$dW = -dU \quad (5a)$$

This is formally identical with the Griffith energy principle of brittle crack propagation eq. (1); but the meaning of eq. (5a) is entirely different. It is merely an expression of Newton's third principle, starting equality of the forces acting upon the elastic and plastic parts of the specimen; it is satisfied identically from the beginning of the plastic crack propagation (or necking) to the point of plastic-elastic instability.

The tangent criterion of instability requires that the derivatives of the yield force F and of the elastic tension G with respect to the extension x must be equal, the differentiation being carried out at constant specimen length. With the values given by eqs. (3) and (4), the expression of the tangent criterion is

$$\frac{d^2W}{dx^2} = -\frac{d^2U}{dx^2} \quad (6)$$

It is seen that the criteria of rapid brittle fracture and of rapid ductile fracture, eqs. (1) and (6), respectively, are fundamentally different; the Griffith principle eq. (1) does not govern high-velocity ductile fracture.

There is a significant practical difference between the two energy criteria of eqs. (1) and (6). Applied to brittle fractures, the Griffith criterion eq. (1) leads to an expression for the tensile strength of a body containing a crack of given length. On the other hand, the tensile force required for ductile fracture cannot be obtained from the criterion eq. (6) of plastic-elastic instability. The ductile breaking force is always the maximum of the load-extension curve, whether or not plastic-elastic instability with rapid fracture occurs. It has to be fed into the criterion, instead of being obtained as the force needed for producing the particular type of plastic deformation which ultimately results in crack propagation and fracture.

3. Summary.

The Griffith energy criterion

$$dW = -dU$$

(dW = crack propagation work, $-dU$ = released elastic energy) cannot be applied to essentially ductile fractures. In particular, it does not represent the condition of rapid ductile fracture propelled by the elastic energy of the specimen. The condition of such fractures is

$$\frac{d^2W}{dx^2} = -\frac{d^2U}{dx^2}$$

where x is the plastic extension accompanying the propagation of the crack.

This paper represents an expanded version of remarks that were stimulated by the work done under Office of Naval Research Contract No. N5ori-07870 and contributed to the Conference on Brittle Fracture Mechanics held at the Massachusetts Institute of Technology on October 15 and 16, 1953, under the auspices of the Committee on Ship Structural Design, advisory to the Ship Structure Committee, National Research Council.

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